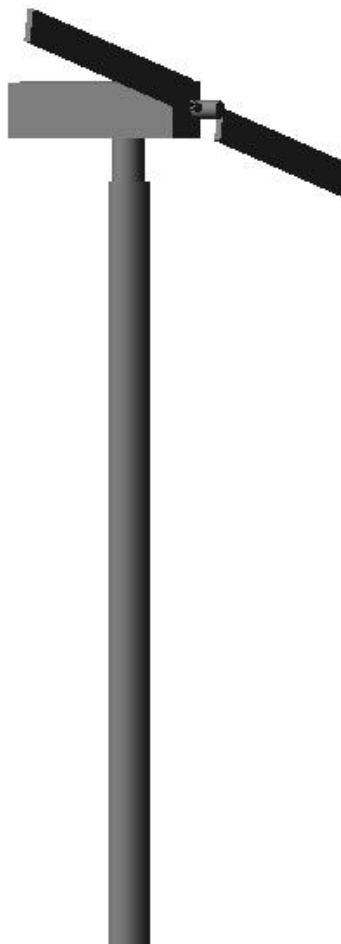


# USER'S GUIDE

to the Wind Turbine Dynamics Computer Program

## YawDyn



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Program date and version  
YawDyn 12.14, 13-January-2003

Prepared for the  
National Renewable Energy Laboratory  
under Subcontract No.  
TCX-9-29209-01

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# **USER'S GUIDE**

## **to the Wind Turbine Dynamics Computer Program**

### **YawDyn**

#### **About this Guide**

This User's Guide is written to assist engineers with the preparation and use of the computer program YawDyn for wind turbine dynamics analysis. This program is written to work with the AeroDyn software package for wind turbine aerodynamics analysis. Together, these programs – YawDyn and AeroDyn - can be used to analyze a simple model of a horizontal axis wind turbine (HAWT). YawDyn has at most four degrees of freedom. AeroDyn is intended to be a general aerodynamics code for HAWT analyses, and can be linked to several other dynamics codes besides YawDyn. A separate User's Guide for AeroDyn is available with that program's release package.

How you use this guide may well depend on your experience with the YawDyn code. Experienced users of the YawDyn code may find the first section outlining the changes in the latest edition of the code sufficient to upgrade and use the new release. New users may find it necessary to look deeper into the guide to help them develop models and set up simulations. Advanced users may use it to understand programming schemes in order to make changes in the code to suit their unique needs. All users will find this guide a useful source to address conventions used in the program, and to help answer other questions. Whatever your experience level with the code, please refer to this guide to try to answer any questions before attempting to contact the authors. Time constraints often do not allow us to personally respond to your queries without at least some delay.

#### **Other Guides in this Series**

This guide is one in a set of three (as of the publication date on the cover), which include:

1. The AeroDyn 12.3 Users' Guide
2. The YawDyn 12.0 Users' Guide (this guide), and
3. The AeroDyn Interface for ADAMS 12.02 User's Guide.

Depending on which programs you intend to run, you may need to refer to other User's Guides in the series. If you plan to use ADAMS with AeroDyn, you will need guides 1 and 3. If you plan to use YawDyn with AeroDyn, you will need guides 1 and 2 (this guide).

## **1.0 Major changes since the last version of YawDyn**

This chapter is provided to assist experienced users of YawDyn with the task of updating their models for use with the latest version of the code. New users can skip to the Introduction. For the latest changes to the code, see the ChangeLog.txt file that is included with the self-extracting archive of the code.

### **1.1 Overview of Version 12.0 Changes**

YawDyn has undergone a major overhaul in terms of functionality beginning with version 12.0. The changes that will most affect users of the code are: 1) previous yawdyn.ipt files are not compatible with version 12.0; 2) the Visual Basic interface YawDynVB is no longer supported and will not work with version 12.0; and 3) the AeroDyn code which is required to run YawDyn is no longer bundled with YawDyn. Details on all of these statements are provided below. Upgrading YawDyn is not a trivial matter. When you plan to update your software, it will be useful to maintain the earlier version while you convert over to version 12.0.

Since AeroDyn is now used with 4 different dynamics codes, it is no longer bundled with YawDyn. By separating the codes and making AeroDyn thoroughly independent, the interface to the codes is more universal, and maintaining the independent codes is easier. This also means you will not be forced to update other codes if YawDyn is updated in the future.

Because of the interplay between AeroDyn and so many other codes, we have found a directory structure that places all the codes under one parent directory to work best for purposes of updating codes and minimizing confusion as to which version of what code is being used. We use a parent directory named “AeroDyn Programs”, and then execute the self-extracting archive for each program in that directory. This places the code in a subdirectory for that program. An “AeroDyn” subdirectory has the AeroDyn code in it, and a “YawDyn” subdirectory the YawDyn code. Maintaining a directory structure such as this helps to keep track of current versions of each code, and simplifies the update of executables dependent on different codes.

YawDyn 12.0 uses Fortran 90 conventions. The “include” files of previous versions have been eliminated and replaced with modules to transport variables between subroutines. The result is that YawDyn now consists of 2 source code files:

1. YawDyn.F90 – main program and subroutines to perform the dynamics calculations.
2. YDMods.F90 – the modules containing variables unique to the YawDyn code.

To create an executable YawDyn 12.0 program, the AeroDyn 12.3 (or later) program files are required. The executable provided with the YawDyn release was created with AeroDyn 12.3.

#### **1.1.1 Changes to Inputs**

The version 11.0 yawdyn.ipt file has been separated into two input files in version 12.0. (A conversion program is available to convert version 11.0 input files to version 12.0.) The yawdyn.ipt file holds all the input parameters used by the YawDyn routines. It bears some resemblance to the lower half of the old yawdyn.ipt file, though the lines have been rearranged. The reader should refer to Table 6.2 for a description of each line of the file. Another input file, aerodyn.ipt, resembles the upper half of the old yawdyn.ipt file and contains all the parameters used by the AeroDyn program. This aerodyn.ipt file is required as input to AeroDyn. Wind and airfoil data files used with AeroDyn have not changed and do not need to be modified to work with YawDyn 12.0.

#### **1.1.2 Changes to Outputs**

The outputs from YawDyn have changed in structure and number. The main output file is still named yawdyn.plt and contains time series data for channels specified in the yawdyn.ipt file. The file now has 3

header lines: 1) program identifier line, 2) column headings, and 3) column units. The available outputs from YawDyn have changed slightly. The rotor torque has been added to the output list. The aileron angle has been eliminated. (The multiple airfoil table function is addressed in the AeroDyn User's Guide.)

The yawdyn.opt file still contains simulation information. It now mimics the information in the yawdyn.ipt and aerodyn.ipt files line for line, and still contains other useful information familiar from earlier versions.

YawDyn now also keeps track of errors and warnings experienced during simulations. These are logged in a file named error.log. This file is cumulative, meaning it is not overwritten, making it possible to keep track of errors over batches of simulations. As a result it is possible for this file to grow large over time, so it may need to be manually deleted after a period of time.

The element.plt file is still an option in AeroDyn. Since it is an AeroDyn output file, more details are provided in the AeroDyn User's Guide.

YawDyn screen outputs have been significantly reduced from previous versions. The amount of information output to the screen was becoming too much to be useful given the speed of current PCs. A few identifying lines are still output during initialization of a simulation, followed a summary of the trim solution. Then, ten lines depicting simulation progress are written. Finally a summary of the simulation CPU time is provided and a tally of the number of errors and warnings encountered. All error and warning messages are written to the screen, as well as to the error.log file.

### 1.1.3 Changes to Dynamics Calculations

Some important changes were made to improve the dynamics calculations in YawDyn. Among these are the addition of inertial terms (to the degree possible) to in-plane and pitching moments. Blade in-plane and pitch inertias are not provided in the YawDyn inputs. Therefore, the in-plane inertia is assumed equal to the out-of-plane inertia and pitch inertia is assumed negligible. In-plane and pitch moments are now calculated in the undeflected blade reference frame (previously they were resolved in the deflected reference frame). This means that there may be crossover between pitch and in-plane moment for a flap-deflected blade. This is considered more realistic since the pitch axis does not usually deflect with the flapping blade. Inertial terms have also been added to the rotor thrust calculation, so it is no longer strictly an aerodynamic load.

### 1.1.4 Other Programming Changes

Most arrays in YawDyn are now dynamically allocated which permits any number of blades, rotational sectors, etc. This allows the simulation of any combination of values without the need to recompile the code.

The YawDynVB Windows application has not been updated for use with YawDyn 12. We do not plan to support this program in the future. We hope this is not a great inconvenience to YawDyn users.

The comments that used to head the YawDyn.for file are now in the file ReadMe.txt distributed with the code. A Change.log file is provided as well to track changes through the versions of the program.

## 1.2 Changes following Version 12.0

Version 12.10 sees the addition of teeter sling in the YawDyn input file. Prior to this, the teeter hinge had to be located at the apex of the rotor cone. See section 6 of this guide for details on this new input.

## **2.0 Introduction**

This document is intended to provide information necessary to prepare inputs for the computer program YawDyn. YawDyn was developed and is maintained with the support of the National Renewable Energy



Laboratory (NREL) National Wind Technology Center (NWTC). YawDyn simulates the yaw motions or loads of a horizontal axis wind turbine with a rigid or teetering hub and two or more blades. The rotor can be simulated in steady winds, discrete time-series winds, or full-field, three-dimensional turbulent wind fields. This document provides a detailed description of each of the program inputs and operating instructions. Sample input and output files are provided for testing the program operation. There is no discussion of the underlying theory or limitations of the models. That discussion is available in a technical report and journal articles [see list of references].

In 1992, the aerodynamics analysis subroutines from YawDyn were modified for use with the ADAMS® program, which is available from Mechanical Dynamics, Inc. (Ann Arbor, MI). The YawDyn aerodynamics routines were extracted from YawDyn as AeroDyn to facilitate interfacing the code with ADAMS. Since then the AeroDyn routines have also been interfaced with the FAST and SymDyn dynamics codes. AeroDyn is now maintained and distributed as a separate code from YawDyn, but is required to run YawDyn. AeroDyn also has a separate User's Guide that should be referenced in order to use YawDyn properly.

This version of the User's Guide is current as of the date and version shown on the cover page. It is applicable only to the specified version of the code. Since the software development is continuing, and significant changes are constantly being made to the programs, the reader should be certain the guide is appropriate to the program version that will be used. Research is ongoing regarding the strengths and limitations of the YawDyn and AeroDyn codes. Users may wish to consult recent wind energy literature to improve their understanding of the code and its accuracy. The change.log file maintains a summary of changes made to the code.

## 2.1 The YawDynVB Program

With version 10.0 of YawDyn we introduced a new Windows interface named YawDynVB. This “point-and-click” interface was updated to version 2.0 for compatibility with YawDyn 11.0. YawDynVB is not compatible with version 12 of YawDyn and will not be supported in the future.

## **3.0 Files Included with YawDyn**

Two files contain the source code for the YawDyn program. They are the main body and dynamics calculation subroutines of the program, YawDyn.F90, and a file containing variables and parameters unique to YawDyn named YDMods.F90. To create a YawDyn executable, the AeroDyn source files must be compiled and linked to YawDyn as well.

The YawDyn data input file is called yawdyn.ipt. The structure of this file has changed from the previous release, and a conversion program is available to update old models. A line by line description of the yawdyn.ipt file is provided in Table 6.2.

Up to three output files are created by YawDyn. The yawdyn.opt file is intended for printing a record of all the input conditions, and a summary of the basic model properties. File YAWDYN.PLT is tabular data intended for plotting the simulation results using a variety of commercially available graphics packages. File error.log contains a running history of the errors and warnings encountered during simulations. This file is cumulative and may grow to be large after a long period of time so should be manually deleted when necessary.

To install YawDyn, place the self-extracting archive YD\_v#### (where #### is the version number identifier) in the appropriate subdirectory (we recommend “AeroDyn Programs”) and execute it either from a command prompt or by double-clicking it in Windows. The files will be extracted to the subdirectory “YawDyn”. A similar procedure is required for the AeroDyn routines (see the AeroDyn User's Guide).

## **4.0 Memory Requirements**

Memory requirements for YawDyn do not seem to be much of a concern given the limits common in today's PCs. Most YawDyn arrays are now dynamically allocated so that only the amount of memory necessary to run the simulation is used. Any memory problems are more likely to be due to AeroDyn, with its more numerous arrays, and those are addressed in the AeroDyn User's Guide.

## **5.0 Nomenclature and Sign Conventions**

The YawDyn analysis is directed toward a wind turbine with the general configuration shown in Figures 5.1 and 5.2 or 5.3. The rotor can have 2 or more blades and the hub is rigid or teetering. The blade flap degree of freedom is modeled using an equivalent hinge and spring arrangement as shown in Figure 5.2 if the hub is rigid (not teetering). The teetering hub configuration is shown in Figure 5.3. When a teetering rotor is simulated, the blades are completely rigid. The only degrees of freedom are the teeter and yaw motion. Effects of undersling and the damping and stiffness characteristics of the teeter stop are included in the teetering model. Delta-three angle cannot be included in the model. The model assumes that all blades are identical in all respects *except* that each blade pitch angle is specified independently. (Blade aerodynamic properties are defined in inputs to the AeroDyn code.)

The definitions of yaw angle ( $\gamma$ ) and wind direction ( $\delta$ ) are shown in Figure 5.1. Both are measured in the same sense, with positive being clockwise when looking down. This is consistent with the compass directions generally used in reporting wind direction. Note however, that yaw is a rotation about the negative Z axis. The yaw angle is the angle the rotor makes with the ground (inertial) coordinate system, not with the instantaneous wind vector. Thus the yaw error (or difference between the compass rotor direction and wind direction) is  $\gamma - \delta$ . When  $\delta = 0$ , the yaw angle and the yaw error are equal.

The rotor can be downwind of the tower (positive  $L_S$  in Figure 5.1 or FORTRAN variable SL) or it can be upwind (negative  $L_S$ ). The axis of rotation of the rotor can be tilted with respect to the horizontal (ground).

The tilt angle  $\tau$  is shown in its positive sense in Figure 5.1. A positive tilt lowers the upwind end of the nacelle. Normally a downwind rotor will have positive tilt while an upwind rotor will have negative tilt (if the hub is raised above the level of the generator in either case).

The rotation of the rotor must be clockwise when viewed looking in the downwind direction. If the rotor to be analyzed actually turns in the counterclockwise direction, the user must be careful interpreting the sign conventions. It is best to consider the position of the blade when it is advancing into the region of increased relative wind speed (due to yaw angle or wind shear) and adjust the signs of the yaw angle and wind shears to be appropriate to this condition.

An example may clarify this topic for YawDyn users. In the example, consider a downwind rotor that spins counterclockwise when viewed from a location that is upwind of the machine. In this case the rotor angular velocity vector (using the right hand rule) is directed from the hub toward the yaw axis and the rotation is opposite that used in the program. Consider also that the wind speed is higher on the left side of the rotor than on the right (when looking downwind). This situation is sketched in the views labeled "actual situation" in Figure 5.5. It is not possible to run the program with a negative (counterclockwise) rotor rpm, so other signs must be adjusted. With yaw and horizontal wind shear the blade will be advancing into the wind when the blade is vertical upwards ( $\psi=180^\circ$ ) and the yaw angle is *negative*. If the rotor spin were clockwise the advancing blade would be at  $\psi=180^\circ$  when the yaw angle is *positive*, and the horizontal shear is *negative*. Thus the change in the sense of rotation requires a change in the sign of the yaw angle and the horizontal wind shear to achieve the same conditions for the blade. This is depicted in the views labeled "model equivalent" in Figure 5.5. To summarize, the actual situation in Figure 5.5 has counterclockwise rotor rotation, a negative yaw angle and positive wind shear. This is modeled with clockwise rotation, positive yaw, and negative horizontal shear. The goal at all times is to keep the orientation of the advancing blade correct.

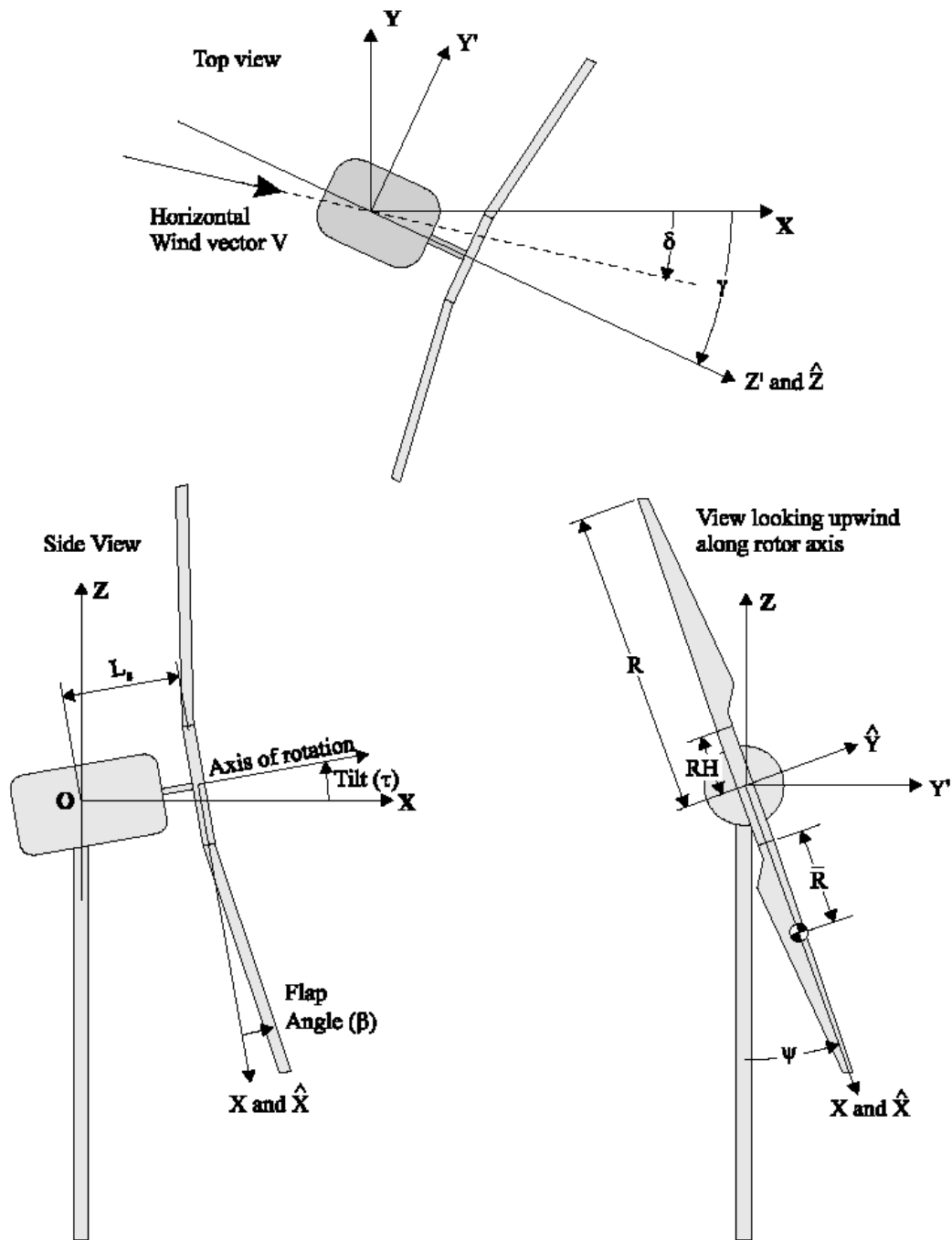


Figure 5.1 View of the HAWT defining selected terms and coordinate systems. All angles are shown in their positive sense. The bold  $X, Y, Z$  axes are fixed in space and are the coordinates in which the wind components are defined ( $V_X, V_Y, V_Z$ ). Note that blade azimuth is zero when the blade is at the 6 o'clock position.

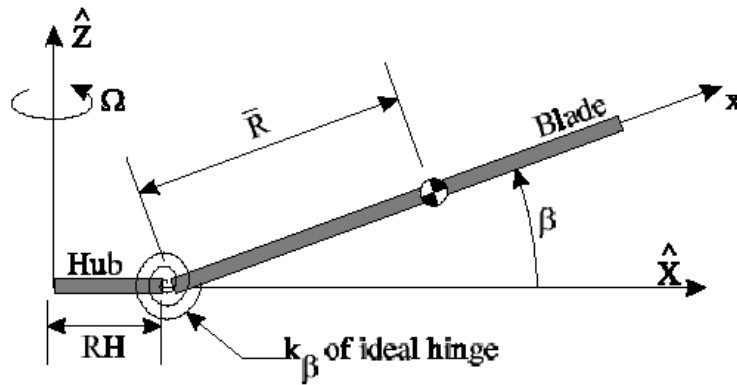


Figure 5.2 The equivalent hinge-spring model for the blade flap degree of freedom

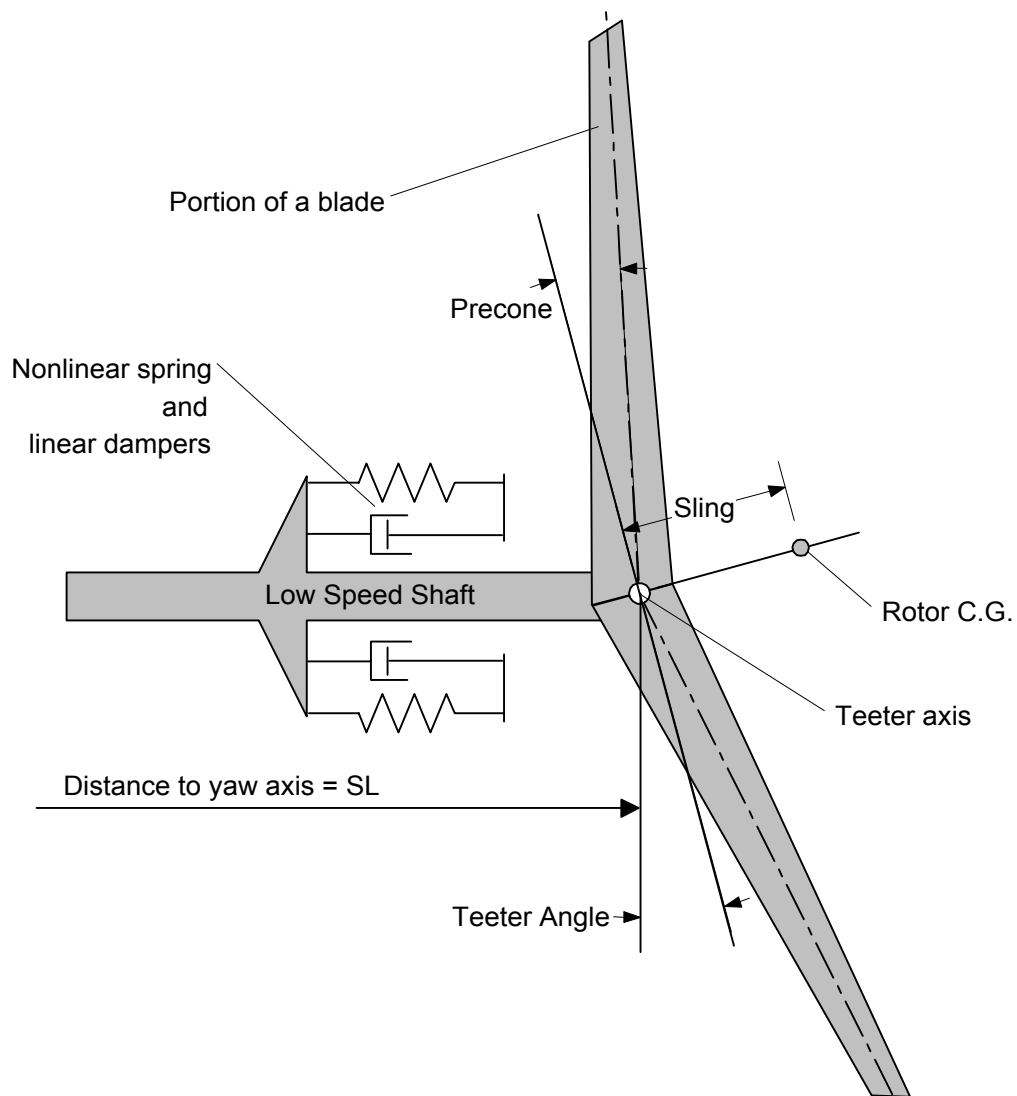


Figure 5.3 The configuration of the teetering hub model. The spring and damper are only active when the teeter deflection exceeds the angle TEE1. The flap angle of blade #1 is the sum of the precone and the teeter angle.

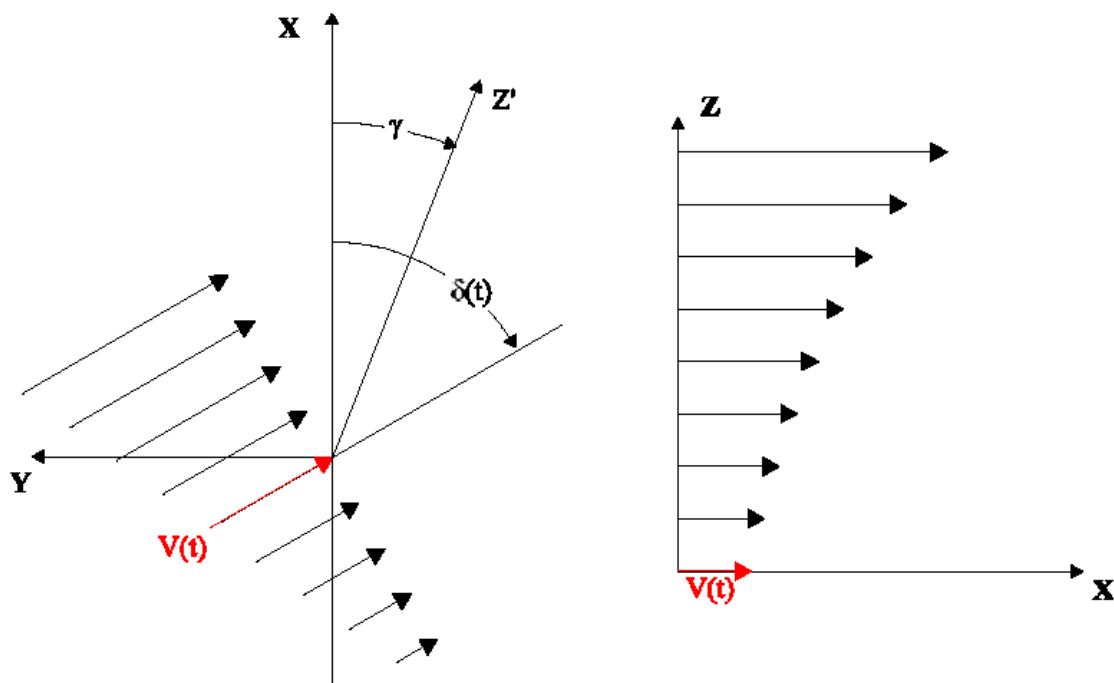


Figure 5.4 Wind shear models Horizontal shear in left sketch, Vertical shear in right sketch. Note the wind direction ( $\delta$ ) and yaw angle ( $\gamma$ ) are both defined with respect to the X axis.

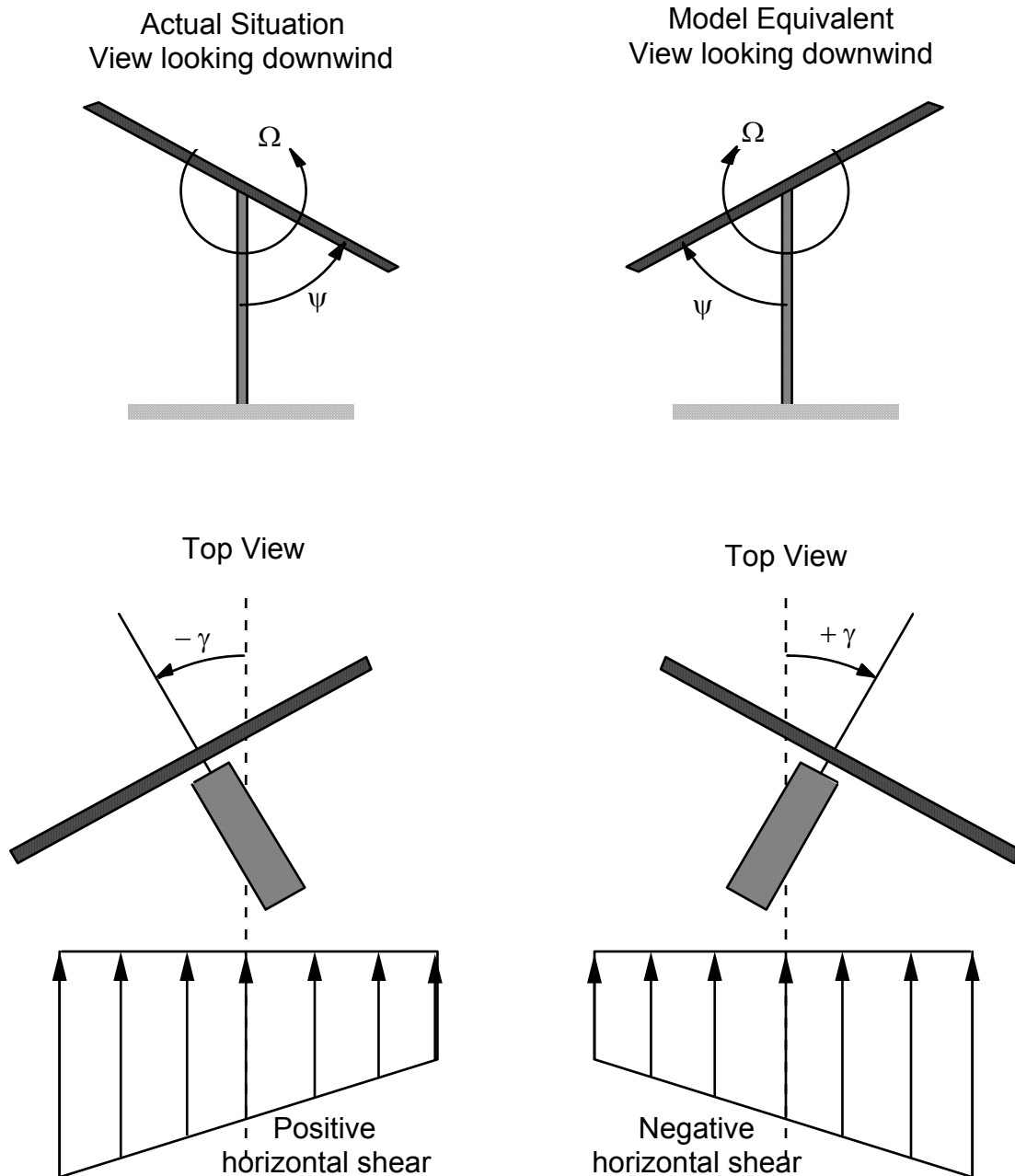


Figure 5.5 Views of example configuration with horizontal wind shear. Left half shows the actual configuration while the right side shows how that configuration can be modeled in YawDyn.

## **6.0 Input Data File Description**

A sample YAWDYN.IPT input data file is given in Table 6.1. A text data file with this name and containing each of these items must be available in the directory or folder from which the program is run. The following paragraphs describe each of the input variables. The formatting is list-directed (or free). There are no restrictions on the spacing of the values other than the order of the variables on a line, the order of the lines, and the presence (absence) of a decimal point in a floating point (integer) value. Values on one line should be separated by one or more spaces or tabs. Each line, except the first and last, can be terminated with a text string to identify that line. Each line must terminate with a return character. Each

line must contain all of the variables specified for that line in the table below. Omission of a value that is not used by the program in that particular run may not result in a runtime error, but the line on which that parameter should be located must be present.

A line-by-line description of the input data file is given in Table 6.2. In this description, the engineering units for each parameter are listed for the program as they are used with English and SI (metric) units. The units used in the simulation are set in the AeroDyn input file. The units in AeroDyn and YawDyn must agree.

Table 6.1 - Sample Input Data File for the NREL Combined Experiment Wind Turbine

```

Combined Experiment Baseline for YawDyn version 12.14
30.0      Time duration of the simulation (sec)
200.0     Number of azimuth sectors used for integration
5         Decimation factor for output printing
1.0000E-02 TOLER, Trim solution tolerance (deg)
3         Number of blades
14.0 14.0 14.0 Initial pitch angles (deg)
4.0      Rotor hub sling (distance from yaw axis to hub; positive downwind) (ft)
0.0      Shaft tilt angle (deg)
3.0      Rotor precone angle (deg)
72.0     RPM, rotor speed in revolutions per minute
0.0      PsiInit, Initial rotor position (zero for Blade 1 down) (deg)
FIXED    Yaw Model: FREE or FIXED yaw system
0.0      Initial yaw angle (deg)
0.0      Initial yaw rate (deg/sec)
1000.0   Mass moment of inertia about yaw axis (slug-ft^2)
0.0      YawStiff, stiffness of yaw spring (lb-ft/rad)
0.0      YawDamp, yaw damping coefficient (lb-ft-sec)
0.0      YawFriction, constant friction moment at yaw axis (lb-ft)
HINGE    Hub model: HINGE, TEETER or RIGID
3.0 3.0 3.0 Initial flap angles (deg)
0.0 0.0 0.0 Initial flap rates (deg/sec)
1.7      RHinge, radius of rotor hub (ft)
5.44     RBar, distance from hinge to blade c.g. (ft)
3.34     Mass of one blade (slug)
178.0    Mass moment of inertia of blade about hinge axis (slug-ft^2)
1.5500E+05 Torsional stiffness of blade root spring (lbf-ft/rad)
0.02     Teeter sling distance of teeter axis upwind of rotor apex (ft)
0.0      Free teeter angle (deg)
0.0      Teeter stiffness, first or linear coeff. (lbf-ft/rad)
0.0      Teeter stiffness, coeff. of deflection (lbf-ft/rad^2)
0.0      Teeter damping coefficient (lbf-ft-sec)
1,20,16,10,30,33,36,24,26,28
  1 = Horizontal wind speed at hub center, len/s. [HHWSpeed]
  2 = Horizontal wind direction at hub center, deg. [HHWDir]
  3 = Nacelle yaw angle, deg. [YawAng]
  4 = Nacelle yaw rate, deg/sec. [YawRate]
  5 = Blade azimuth angle (0 when blade 1 down), deg. [AzimAngB1D]

portion deleted for brevity, see the sample file

45 = Blade 3 in-plane mom., kiloforce*len.
46 = Blade 1 pitching mom., kiloforce*len.
47 = Blade 2 pitching mom., kiloforce*len.
48 = Blade 3 pitching mom., kiloforce*len.

```

Table 6.2 - Descriptions of YawDyn Input File Parameters

<u>ID Number</u> <sup>1</sup>	<u>Units</u> <sup>2</sup>	<u>Description</u>
1  TITLE	--	Any character string (up to 80 characters) to identify the system being analyzed. This also serves as an aid to identifying the contents of the data file.
2  ENDTIME	sec	The total time which will be simulated in the solution. This value determines the number of rotor revolutions to be simulated according to the relation Total Time * RPM / 60=N. RPM is specified below (ID#10).
3  SECTOR	--	The rotor disc is divided into 'SECTOR' equally spaced, pie-wedge sectors for the time-integration. The value should be a positive, whole number. The time step is determined from the floating-point value SECTOR using the equation $\Delta t = 60/(\text{SECTOR} \times \text{RPM})$ . Typically 60-90 sectors are sufficient if the flap degree of freedom is neglected and 150-200 sectors are sufficient if the flap dof is included. As the blade stiffness increases in YawDyn the value of SECTOR must increase as well. If the program will not converge to a trim solution, increase SECTOR. When the program is run in free-yaw the value for SECTOR should be increased if a stiff blade is flapping in the simulation. A value between 600 and 1500 may be needed.
4  IPRINT	--	The decimation factor for data output. Typically, writing every 5th to 10th time step (IPRINT=5 or 10) will provide output data with adequate resolution, but should be set to your specific needs.
5  TOLER	deg	The tolerance used in checking for a trim solution. The trim solution will be found when the root-mean-square difference in flap angles between two sequential rotor revolutions is less than TOLER for all blades. Typically, TOLER should be 0.01-0.02° for a rigid hub and 0.1-0.2° for a teetering hub. If the solution will not converge, try increasing SECTOR or, as a last resort, increasing TOLER.
6  B	--	Number of blades, B=2 or more, except the teetering rotor must have B=2.
7  PITCH(1)	deg	The pitch angles of each blade. Enter a value for each blade, separated by spaces or tabs. The sign convention follows the normal wind-turbine convention, i.e. positive pitch rotates the leading edge of the blade into the wind (toward feather). Negative pitch tends to move the blade toward stall. The pitch value rotates the entire blade. The values need not be the same for all blades, and a value must be entered for each blade.

<sup>1</sup> This column contains a sequential number, the ID number, and a name. The name represents the variable name in most cases. However, in the case of inputs that control a program option, the allowable inputs are listed.

<sup>2</sup> Units are specified for English system in the first line and SI units in the second line (if different). The unit identifier is found in the AeroDyn input file.



8	ft	The distance from the yaw axis to the center of the hub. A positive value is used for a downwind rotor, a negative value for an upwind rotor. The teeter axis is always located at the center of the hub, though it need not coincide with the rotor center of gravity.
SL	m	
9	deg	The tiltangle of the rotor axis of rotation. The sign convention is <u>not</u> consistent with the coordinate system. That is, positive tilt is a rotation about the negative Y'-axis. Positive tilt lowers the upwind end of the nacelle. A downwind rotor will have positive tilt in the normal situation where the hub is tilted upwards. An upwind rotor will normally have negative tilt (again, with the hub tilted upwards).
TILT		
10	deg	Blade precone angle. Coning is positive when the coning moves the blade tips downwind relative to the hub. (Positive coning normally gives centrifugal relief of blade root flap moments.)
PC		
11	rpm	Rotor rotation speed in revolutions per minute. Must be greater than zero; very small values should be avoided as they may cause problems as well.
RPM		
12	deg	Initial azimuth position of the rotor at the start of the YawDyn simulation in the convention of YawDyn (see Figure 5.1). A value of 0 positions the rotor with blade 1 down (in the 6 o'clock position), which was the default starting position before this parameter was added in version 11.0. Since the rotor in YawDyn spins clockwise looking downwind, 90 degrees is blade 1 horizontal and left of the rotational axis looking downwind (the 9 o'clock position), etc.
PsiInit		
13	--	An input to determine whether the simulation is for fixed yaw rate, or free-yaw operation. If you enter FIXED, the system operates at a fixed yaw rate equal to the initial yaw rate (YawRate, ID#15 below) specified further below in the file. For fixed yaw, use <i>FIXED and set the yaw rate to zero</i> . In the condition of a non-zero constant yaw rate, friction and damping are taken into account, but the yaw torsional stiffness will be set to zero. If you enter FREE, then the system is constrained by the yaw torsional spring. If the spring stiffness (YAWSTF, ID#17 below) is zero, then the system is free-yawing.
FIXED or FREE		
14	deg	Initial yaw angle for the solution. When a yaw stiffness is specified and the program is run for "free yaw", this angle also specifies the undeflected position of the torsion spring. For "fixed yaw" (FIXED (ID#13) with zero yaw rate specified below) this is the angle at which the nacelle is positioned for the entire simulation.
YawAng		
15	deg/s	For "free yaw," this is the initial yaw rate for the solution. <u>For "fixed yaw," this parameter must be set to zero.</u> If you specify FIXED (ID#13), and YawRate is non-zero, the simulation will run at a <i>constant yaw rate</i> , and the yaw torsional spring stiffness will be set to zero (friction and damping are taken into account).
YawRate		

16	slug-ft <sup>2</sup>	Mass moment of inertia about the yaw axis of the main frame, nacelle and those portions of the rotor that are not participating in the flap or teeter motion (e.g. the hub of a rigid rotor). YI represents the total moment of inertia of all the yawing mass <u>except the blades</u> . For a teetering rotor YI does <u>not</u> include the hub inertia because the hub is moving with the blades as they teeter. For a rigid or flapping rotor YI includes the hub mass. When the model is FIXED (ID#13), this value is ignored (no yaw accelerations are calculated for fixed yaw rate operation).
YI	kg-m <sup>2</sup>	
17	ft-lbf/rad	The torsional spring constant of the yaw drive or yaw brake system. This variable can be used to represent an equivalent stiffness of the yaw drive system and the tower (the overall effective torsional stiffness between the nacelle and ground). The value is only used when “free yaw” is simulated (ID#13 = FREE), but the line must always be present in the data file. If the actual system stiffness is very high, then the system should be run in “fixed yaw” (ID#13 = FIXED <i>and</i> zero yaw rate (i.e., YawRate (ID#15) = 0.0)).
YAWSTF	N-m/rad	
18	ft-lbf-sec	The linear yaw damping coefficient. The yaw moment (N-m or ft-lbf) due to mechanical damping on the yaw axis is AV multiplied by the yaw rate in radians/sec. This value is used in both “free yaw” and “fixed (non-zero) yaw rate” simulations. Although not used for “fixed yaw,” this line must always be present.
AV	N-m-sec	
19	ft-lbf	The sliding friction yaw moment. A constant yaw moment due to friction. The moment always opposes yaw motion. Note this is <u>not</u> a friction coefficient. This value is used in both “free yaw” and “fixed (non-zero) yaw rate” simulations. Although not used for “fixed yaw,” this line must always be present.
AF	N-m	
20	--	An input to determine whether the rotor has a rigid, flapping or teetering rotor. There are three possible entries, HINGE, TEETER, or RIGID. The RIGID option creates a model with only a yaw degree of freedom. This will allow a faster simulation for examining power output or other parameters that are not greatly influenced by blade flapping motion. A value of HINGE creates the flapping hinge model. If you enter TEETER then the rotor will have a teeter hinge at the center of the hub (a teetering rotor must have two blades).
HINGE, TEETER or RIGID		
21	deg	Initial flap angle for each blade. Enter a value for each blade, separated by spaces or tabs. (For a teetering rotor, only the value for blade #1 is read.) The initial flap and flap rate (next line) are important to the efficient convergence to a rotor trim solution. It is suggested that when a rotor is analyzed for the first time, the flap angles should all equal the precone angle and the flap rates should all be zero. This will usually result in a slow but accurate convergence to a trim solution. When the trim solution is found, the values of flap and flap rate are output to the CRT. These values can be used in subsequent runs of the program to significantly reduce the time required to find the trim solution. When the rotor is RIGID (ID#20), these values are ignored by the program.
QP array		
22	deg/s	Initial flap rate for each blade. Enter a value for each blade, separated by spaces or tabs. (For a teetering rotor, only the value for blade #1 is read.) When the rotor is RIGID (ID#20), these values are ignored by the program.
QP array		

23	ft	Hub radius or offset. The distance from the axis of rotation to the hinge axis, measured perpendicular to the axis of rotation. This value affects both the dynamic and aerodynamic analysis. When TEETER (ID#20) is selected, this value is ignored and RH is set to zero for the teetering rotor.
RH	m	
24	ft	The distance along the blade from the hinge axis to the blade center of gravity. For a teetering rotor, this is the distance from the teeter axis (see Figure 5.3) to the center of gravity of the combination of one blade and one-half of the hub.
RB	m	
25	slugs	The mass of <u>one</u> blade. When the rotor has a teetering hub the mass of one blade plus half of the hub mass should be entered here. That is, for a teetering rotor only, this value represents one-half of the rotor mass.
BM	kg	
26	slug-ft <sup>2</sup>	The blade mass moment of inertia about the flap axis. For a flapping hinge or rigid rotor, this value is the inertia about the hinge axis. If the rotor is teetering then BLINER represents one-half the moment of inertia of the entire rotor (including hub and any concentrated masses) about the teeter axis (see Figure 5.3).
BLINER	kg-m <sup>2</sup>	
27	ft-lbf/rad	The torsional spring constant of the equivalent flapping hinge spring at the blade root. This value is named $k_\beta$ in the reports and literature and in Figure 5.2. When using the TEETER (ID#20) option this line is ignored. When using the RIGID (ID#20) option, this value is only used to calculate the value of the flap natural frequency and does not affect dynamics.
FS	N-m/rad	
28	ft	The location upwind of the rotor apex where the teeter hinge is located. . Used for a teetering rotor only, but this line must be present in the file.
TEESL	m	
29	deg	The teeter angle at which the first contact with the teeter “stop” is made. No mechanical teeter moment is applied at the hub if the absolute value of the teeter angle is less than TEE1. For teeter angles greater than TEE1, a nonlinear spring and a linear damper are active. See Figure 5.3 for a sketch of the teetering hub configuration. Used for a teetering rotor only, but this line must be present in the file.
TEE1		
30	ft-lbf/rad	The first (linear) coefficient in the quadratic equation that describes the teeter spring or “stop”. The moment applied by the teeter spring is given as $M = \text{SPRNG1} * \delta + \text{SPRNG2} * \delta^2$ Where $\delta$ is the spring deflection in radians and the sign is chosen as appropriate for the direction of deflection. Used for a teetering rotor only, but this line must be present in the file.
SPRNG1	N-m/rad	
31	ft-lbf/rad <sup>2</sup>	The second coefficient in the equation that describes the teeter spring. SPRNG1 and SPRNG2 determine the shape of the parabolic spring which represents the teeter stop. Used for a teetering rotor only, but this line must be present in the file.
SPRNG2	N-m/rad <sup>2</sup>	
32	ft-lbf-sec	The coefficient of the linear teeter damping. The damper is active for all teeter angles greater than TEE1. The teeter moment (N-m or ft-lbf) due to mechanical damping on the teeter axis is TDAMP multiplied by the teeter rate in radians/sec. Used for a teetering rotor only, but this line must be present in the file.
TDAMP	N-m-sec	

---

33	--	A numeric list of the channels to be output to the yawdyn.plt file. The channels available are listed at the end of the sample input file provided, as well as in Table 6.3. This is the last line read by YawDyn. <u>You must list the channels you want to output.</u> At least one channel must be listed in order for YawDyn to run. Commas, spaces, tabs, or other delimiters should be used to separate items in the list. The line must not contain any comments.
----	----	--

---

Table 6.3 - List of Available Output Channels

Channel Number	Description	Units - SI (English)	yawdyn.plt Column Headings
1	Horizontal wind speed at hub center	m/sec (ft/sec)	HHWSpeed
2	Horizontal wind direction at hub center	deg	HHWDir
3	Nacelle yaw angle	deg	YawAng
4	Nacelle yaw rate	deg/sec	YawRate
5	Blade azimuth angle (0 when blade 1 down)	deg	AzimAngB1D
6	Blade azimuth angle (0 when blade 1 up)	deg	AzimAngB1U
7	Teeter angle	deg	TeeterAng
8	Teeter rate	deg/sec	TeeterRate
10	Blade 1 flap angle	deg	FlapAng1
11	Blade 1 flap rate	deg/sec	FlapRate1
12	Blade 2 flap angle	deg	FlapAng2
13	Blade 2 flap rate	deg/sec	FlapRate2
14	Blade 3 flap angle	deg	FlapAng3
15	Blade 3 flap rate	deg/sec	FlapRate3
16	Rotor power	kW	Power
17	Rotor torque	N-m (ft-lbf)	Torque
20	Nacelle yaw moment	N-m (ft-lbf)	YawMom
21	Nacelle yaw moment	kN-m (kft-lbf)	YawMomK
22	Teeter hub moment exerted by teeter stops	N-m (ft-lbf)	TeeStMom
23	Teeter hub moment exerted by teeter stops	kN-m (kft-lbf)	TeeStMomK
24	Rotor thrust	N (lbf)	Thrust
25	Rotor thrust	kN (klbf)	ThrustK
26	Lateral hub force	N (lbf)	HforceY
27	Lateral hub force	kN (klbf)	HforceYK
28	Vertical hub force	N (lbf)	HforceZ
29	Vertical hub force	kN (klbf)	HforceZK
30	Out-of-plane bending moment for blade 1	N-m (ft-lbf)	OutPlMom1
31	Out-of-plane bending moment for blade 2	N-m (ft-lbf)	OutPlMom2
32	Out-of-plane bending moment for blade 3	N-m (ft-lbf)	OutPlMom3
33	In-plane bending moment for blade 1	N-m (ft-lbf)	InPlMom1
34	In-plane bending moment for blade 2	N-m (ft-lbf)	InPlMom2
35	In-plane bending moment for blade 3	N-m (ft-lbf)	InPlMom3
36	Pitching moment for blade 1	N-m (ft-lbf)	PitchMom1
37	Pitching moment for blade 2	N-m (ft-lbf)	PitchMom2
38	Pitching moment for blade 3	N-m (ft-lbf)	PitchMom3
40	Out-of-plane bending moment for blade 1	kN-m (kft-lbf)	OutPlMom1K
41	Out-of-plane bending moment for blade 2	kN-m (kft-lbf)	OutPlMom2K
42	Out-of-plane bending moment for blade 3	kN-m (kft-lbf)	OutPlMom3K
43	In-plane bending moment for blade 1	kN-m (kft-lbf)	InPlMom1K
44	In-plane bending moment for blade 2	kN-m (kft-lbf)	InPlMom2K
45	In-plane bending moment for blade 3	kN-m (kft-lbf)	InPlMom3K
46	Pitching moment for blade 1	kN-m (kft-lbf)	PitchMom1K
47	Pitching moment for blade 2	kN-m (kft-lbf)	PitchMom2K
48	Pitching moment for blade 3	kN-m (kft-lbf)	PitchMom3K

## **7.0 User Operation at Runtime and the YAWDYN.PLT file**

No user input is required while the program is running (unless unforeseen errors are generated). The CRT will display information on the status of the calculations and a few statements about the run conditions so that the calculations can be stopped if the desired conditions are not being run. The lines below are typical of what will be seen as the program executes (though the details may not match the sample input file provided above).

The search for the trim solution will continue until the "RMS ERROR" values for all blades are less than the "TOLER" value from the input file. If 50 trim revolutions are run before the solution converges to a trim condition the calculation will be aborted. If this occurs, use different initial conditions or try a larger tolerance for the trim criteria.

First the program displays the TITLE information. It then proceeds with the calculations and writes information to the screen concerning progress and results of those calculations. Ten equally spaced time steps over the course of the simulation have data written to the CRT. This data includes simulation time (T, in seconds), rotor azimuth (AZ, in degrees), nacelle yaw angle in (YAW, in degrees), nacelle yaw rate (YR, in degrees per second), blade 1 flap angle (FLAP, in degrees) and blade 1 flap rate (FR, in degrees per second). (Some details may have changed slightly since this CRT transcript was copied into the User's Guide, so your display will not match this one perfectly. The general content and the meaning of the various outputs have not changed.)

Running AeroDyn(12.51, 13-Jan-2003) in YawDyn(12.14, 13-Jan-2003).

Heading of the yawdyn.ipt file:  
Combined Experiment Baseline in ENGLISH units for YawDyn version 12.1

Heading of the aerodyn.ipt file :  
Combined Experiment Baseline for YawDyn version 12.1

Detected full-field wind files:  
"turb.wnd" and  
"turb.sum"

Reading a 6x6 grid of 65.62 fps full-field wind data.

800 records processed. FF wind data rate is 20 Hz.

Using 39.95 of 39.95 seconds of this FF wind file.

YawDyn using English units as per AeroDyn input.

Seeking trim solution for flap DOF  
AZMTH= 85. FLAP= 0.2

portion deleted for brevity, see the sample file

TRIM REVOLUTION	5				
BLADE #1	FLAP=	0.38	FLAP RATE=	-4.01	RMS ERROR= 0.00098
BLADE #2	FLAP=	0.26	FLAP RATE=	-0.63	RMS ERROR= 0.00306
BLADE #3	FLAP=	0.41	FLAP RATE=	2.77	RMS ERROR= 0.00262

Initial values for transient solution:

BLADE	FLAP	FLAP RATE
1	3.401	-4.011
2	3.262	-0.631
3	3.404	2.772

Starting transient solution...

T=	3.0	AZ= 216.	YAW=	0.0	YR=	0.0	FLAP=	3.4	FR= -0.4
T=	6.0	AZ= 72.	YAW=	0.0	YR=	0.0	FLAP=	3.6	FR= -4.1
T=	9.0	AZ= 288.	YAW=	0.0	YR=	0.0	FLAP=	3.4	FR= -0.3
T=	12.0	AZ= 144.	YAW=	0.0	YR=	0.0	FLAP=	3.5	FR= -0.2

```

T= 15.0  AZ= 0.   YAW= 0.0  YR= 0.0  FLAP= 3.4  FR= -5.5
T= 18.0  AZ= 216. YAW= 0.0  YR= 0.0  FLAP= 3.4  FR= 1.1
T= 21.0  AZ= 72.  YAW= 0.0  YR= 0.0  FLAP= 3.6  FR= -4.1
T= 24.0  AZ= 288. YAW= 0.0  YR= 0.0  FLAP= 3.3  FR= 0.8
T= 27.0  AZ= 144. YAW= 0.0  YR= 0.0  FLAP= 3.5  FR= 3.5
T= 30.0  AZ= 0.   YAW= 0.0  YR= 0.0  FLAP= 3.4  FR= -2.6

```

Simulation Timing:

```

Total Clock Time:      2.015 seconds
Startup Clock Time:    0.296 seconds
Transient Clock Time:   1.719 seconds
Transient Sim Time:     30.000 seconds

```

```

Sim/Clock Time Ratio:  17.452

```

Finished.

```

0 warnings recorded in error.log file for this simulation.
0  errors recorded in error.log file for this simulation.

```

The output file YAWDYN.PLT is useful for plotting predictions as a function of time. The first line of this file declares that YawDyn and AeroDyn (including version numbers and dates) created it, and the date and time it was created. A line of column headings follows this, which in turn is followed by the column units. Time series data starts on line 4. Tabs are used to separate the columns, allowing many spreadsheet and graphics software packages, as well as post-processing routines to easily read the file.

The YAWDYN.PLT file can contain a variety of response data, dependent upon the channels selected for output in the yawdyn.ipt file. The column headings may not be self-explanatory, so check the outputs selected in yawdyn.ipt and Table 6.3 for clarification.

The lateral and vertical hub forces are net aerodynamic forces. They are defined with respect to the rotor plane (the plane perpendicular to the rotor shaft). The horizontal and vertical force components are in the plane of the rotor. These forces do not include inertial forces, and are therefore not the net lateral and vertical forces. All other forces include aerodynamic, gravity and inertial forces. The in and out of plane moments are defined with respect to the plane of rotation and will only equal the “flap” moment or “edge” moment for zero pitch.

The optional ELEMENT.PLT file contains wind and aerodynamic data for elements selected in the aerodyn.ipt file. For more information on this output file, see the AeroDyn User’s Guide.

YawDyn also produces a summary file named YAWDYN.OPT, which reiterates the inputs, and provides other useful information. A Sample YAWDYN.OPT file is shown in Table 7.1.

**Table 7.1 - Sample YAWDYN.OPT file from Program YawDyn 12.0 with AeroDyn 12.3**  
Using input file given in Table 6.1.

This file was generated by AeroDyn(12.51, 13-Jan-2003) in YawDyn(12.14, 13-Jan-2003) on 13-Jan-2003 at 16:36:56.

Inputs read in from aerodyn.ipt:

```

Combined Experiment Baseline for YawDyn version 12.1
ENGLISH          Units for input and output
BEDDOES          Dynamic stall model          [Beddoes]
USE_CM           Aerodynamic pitching moment model [Pitching Moments calculated]
EQUIL           Inflow model                  [Equilibrium]
SWIRL           Induction factor model         [Normal and Radial flow induction
factors calculated]
0.005           Convergence tolerance for induction factor
PRAND           Tip-loss model                 [Prandtl model]
NONE            Hub-loss model                [NO hub-loss calculated]
"turb"          is the Full-field wind file root
55             Wind reference (hub) height, ft
0.1            Tower shadow centerline velocity deficit
3             Tower shadow half width, ft
4             Tower shadow reference point, ft
0.002          Air density, slug/ft^3
1.625e-4       Kinematic air viscosity, ft^2/'sec
[NOT USED]     Time interval for aerodynamic calculations, sec
1             Number of airfoil files used. Files listed below:
"S809_Cln.dat"
10            Number of blade elements per blade
RELM(ft)       Twist(deg)      DR(ft)      Chord(ft)  File IDElem DataRELM and
Twist ignored by ADAMS (but placeholders must be present)
0.74          0      1.48      1.5      1
2.22          0      1.48      1.5      1      PRINT
3.7           0      1.48      1.5      1
5.18          0      1.48      1.5      1      PRINT
6.66          0      1.48      1.5      1
8.14          0      1.48      1.5      1      PRINT
9.62          0      1.48      1.5      1
11.1          0      1.48      1.5      1      PRINT
12.58         0      1.48      1.5      1
14.06         0      1.48      1.5      1      PRINT

```

Full-field wind file info:

```

Read in 6x6 grid of 65.62 fps turbulence data.
800 records processed with a time step of 0.05 seconds per record.
39.95 sec. total time duration in this turbulence file

```

BEDDOES DYNAMIC STALL PARAMETERS:

```

CN SLOPE      7.1250
STALL CN (UPPER) 1.9408
STALL CN (LOWER) -0.8000
ZERO LIFT AOA  -0.3800
MIN DRAG AOA   2.0000
MIN DRAG COEFF 0.0116

VORTEX TRANSIT TIME FROM LE TO TE 11.00000
PRESSURE TIME CONSTANT 1.700000
VORTEX TIME CONSTANT 6.000000
F-PARAMETER TIME CONSTANT 3.000000

```

Blade element aerodynamic time series data written to file.

Acceleration due to gravity = 32.174 ft/sec^2

Inputs read in from yawdyn.ipt:

```

Combined Experiment Baseline in ENGLISH units for YawDyn version 12.1
30      Time duration of the simulation (sec)
200     Number of azimuth sectors used for integration
5       Decimation factor for output printing

```



```

0.01          TOLER, Trim solution tolerance (deg)
3             Number of blades
14 14 14      Initial pitch angles (deg)
4             Rotor hub sling (distance from yaw axis to hub; positive downwind) (ft)
0             Shaft tilt angle (deg)
3             Rotor precone angle (deg)
72            RPM, rotor speed in revolutions per minute
0             PsiInit, Initial rotor position (zero for Blade 1 down) (deg)
FIXED         Yaw Model: FREE or FIXED yaw system [FIXED-YAW rate analysis]
0             Initial yaw angle (deg)
0             Initial yaw rate (deg/sec)
0             Mass moment of inertia about yaw axis (slug-ft^2)
0             YawStiff, stiffness of yaw spring (lb-ft/rad)
0             YawDamp, yaw damping coefficient (lb-ft-sec)
0             YawFriction, constant friction moment at yaw axis (lb-ft)
HINGE        Hub model: HINGE, TEETER or RIGID [Hinged rotor analysis]
3 3 3         Initial flap angles (deg)
0 0 0         Initial flap rates (deg/sec)
1.7           RHinge, radius of rotor hub (ft)
5.44          RBar, distance from hinge to blade c.g. (ft)
3.34          Mass of one blade (slug)
178           Mass moment of inertia of blade about hinge axis (slug-ft^2)
1.55e+5       Torsional stiffness of blade root spring (lb-ft/rad)
0             Teeter Sling; distance of teeter axis upwind of rotor apex (ft)
0             Free teeter angle (deg)
0             Teeter stiffness, first or linear coeff. (lb-ft/rad)
0             Teeter stiffness, coeff. of deflection (lb-ft/rad^2)
0             Teeter damping coefficient (lb-ft-sec)
1,20,16,10,30,33,36,24,26,28      List of Outputs (see below)
HHWSpeed(ft/s)
YawMom(lb-ft)
Power(kW)
FlapAng1(deg)
OutPlMom1(lb-ft)
InPlMom1(lb-ft)
PitchMom1(lb-ft)
Thrust(lb)
HForceY(lb)
HForceZ(lb)

Blade Length = 14.8 (ft)
Rotor radius = 16.48 (ft)
Hub Height   = 55 (ft)

Blade flapping natural frequency = 4.7 (Hz)
Blade rotating natural frequency = 4.060922 P

Flap Moment is the blade deflection times the spring stiffness.
Yaw Moment is the net applied moment.

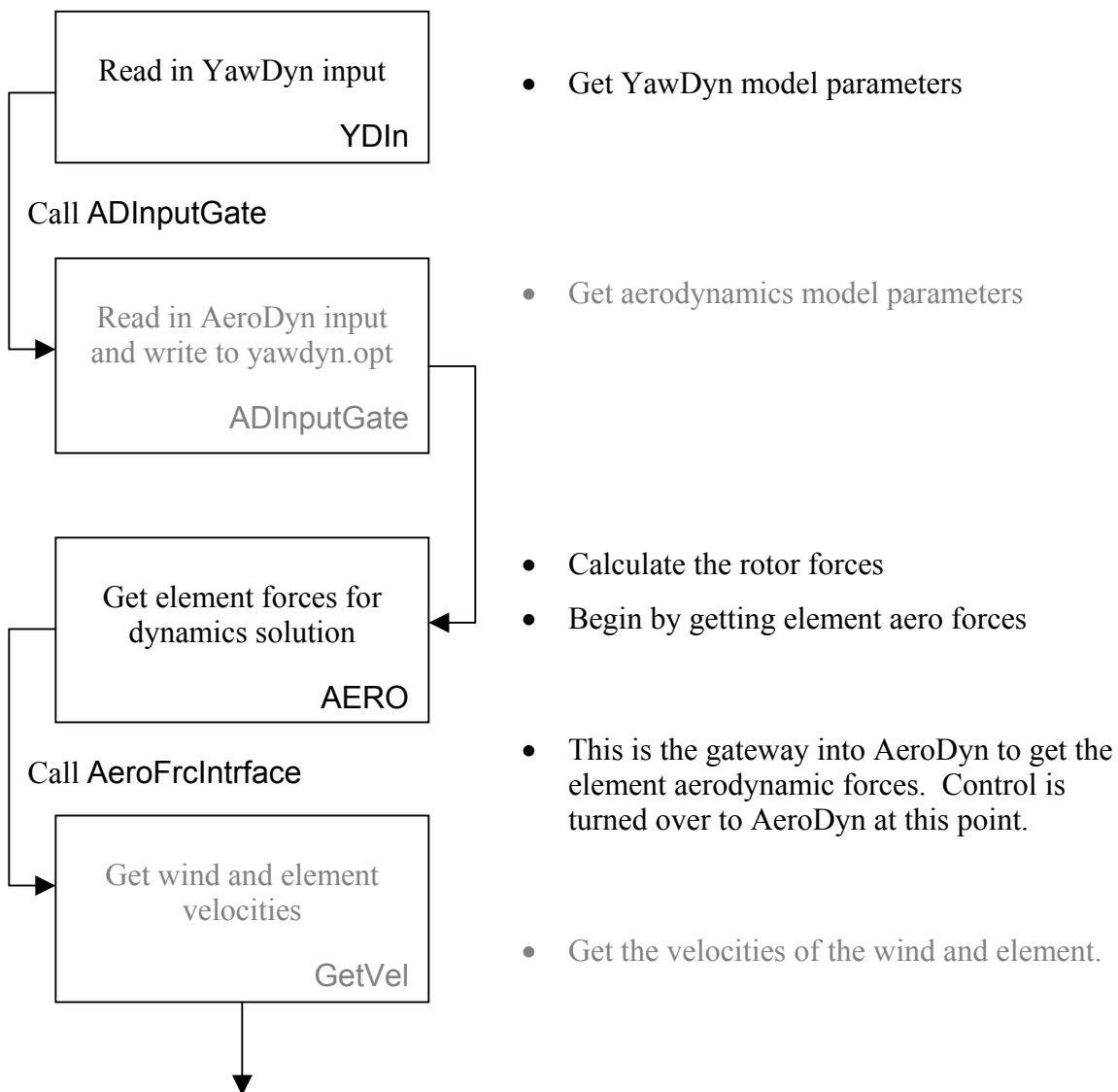
Total time duration simulated = 30 seconds,
consisting of 7200 points with 200 points per revolution.

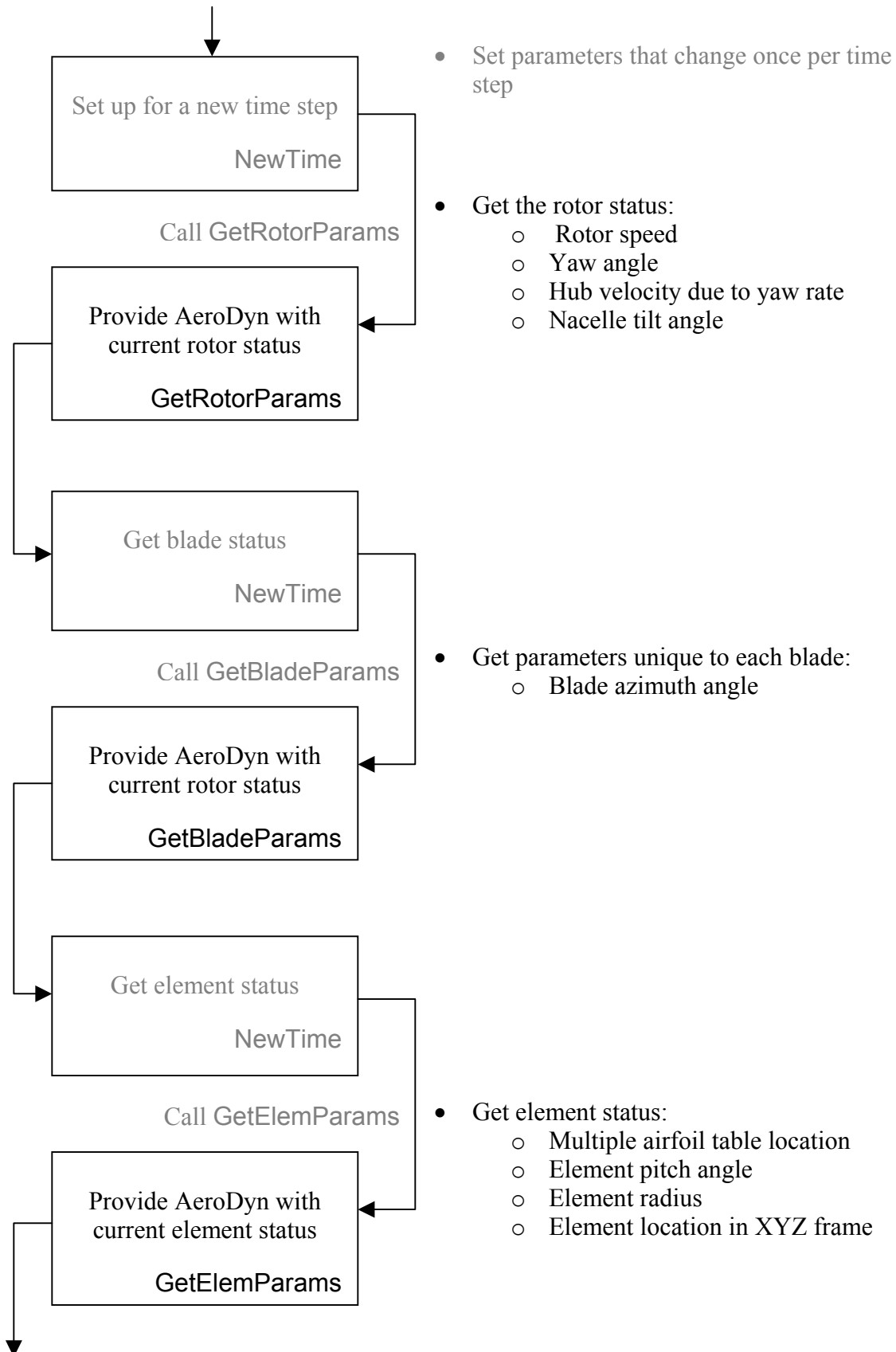
```

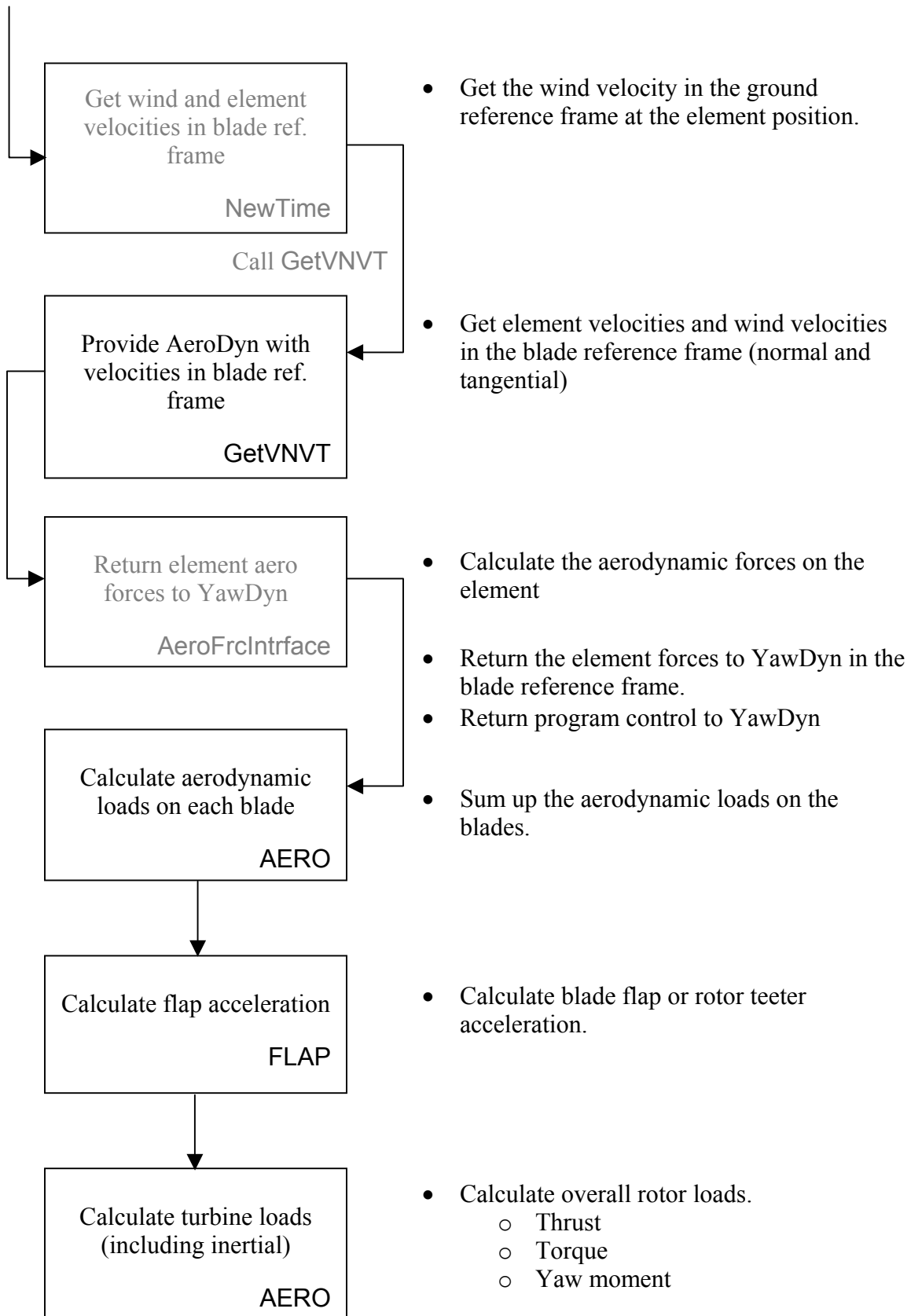
## Appendix A. Top-Level Flow Chart of the YawDyn Dynamics Calculations

This appendix provides a simplified flow chart for the YawDyn dynamics calculations. The purpose of the chart is to familiarize the user with the method that is used, especially the interaction between YawDyn and AeroDyn. AeroDyn processes are written in *gray*. The chart does not map the flow of the entire program, nor does it use the format of traditional software flowcharts. The chart focuses on the operations rather than the code or subroutine structure. The name of certain subroutines in which a procedure is performed are provided in *Arial Font* throughout the chart. This is intended to assist users who wish to examine the details within the subroutines.

The procedure to calculate aerodynamic forces in AeroDyn is completed once for each blade element at each time step. Other subroutines, some shown in this chart, handle input and output of data and integration of the equations of motion. The output steps are not depicted in this chart, though there is one call to AeroDyn to output element data if desired. This is the only interaction between YawDyn and AeroDyn not depicted.







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